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WELBORE USER'S MANUAL

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Introduction

WELBORE is a computer code for simulating transient, one-dimensional two-phase or single-phase non-isothermal fluid flow in a wellbore. The program uses a partially implicit method to solve the finite difference approximation of the Navier-Stokes equations of mass, momentum, and energy conservation. Terms that would impose a severe time restriction, such as the compressibility terms are evaluated implicitly while other terms are expressed in an explicit manner. The convection effects are represented with a conserving upwind finite difference. Both the slip between the phases (when the flow is two-phase) and the frictional losses are given as empirical correlations. The primary thermodynamic variables used in solving the equations are the pressure and specific energy. An equation of state subroutine provides the density, quality, and temperature. The heat loss out of the wellbore is calculated by solving a radial diffusion equation for the temperature changes outside the bore. The calculation is done at each node point in the wellbore. Also the code has been coupled with a single phase radial flow reservoir model. A version of the wellbore code coupled with a two-phase rservoir model will be available in the near future.

The important difference between this program and other reported wellbore models is that a steady state is not assumed, i.e., the mass into the well does not necessarily equal the mass out of it. Nevertheless, a steady state solution can be obtained. A transient wellbore model with or without a reservoir model is useful in understanding well test results. One can eliminate the response of the fluid in the well in the analysis of well test data, i.e., given the wellhead flow rate or wellhead pressure and the downhole pressure, the sandface flow rate can be calculated. By knowing the actual reservoir flow, one can determine reservoir properties by using a variable well test analysis technique to reduce the transient pressure data. Such a method reduces the time of a well test because data taken when wellbore storage is important can still be used. It is possible to study early transient changes in the wellbore. It has been shown that the early time data can be altered so that a unit slope of log P vs. log t is not necessarily measured (Miller, 1979). When kh/μ is relatively large, say 10 D-m, the reservoir can respond with a substantial part of the surface flowrate while the transient pressure changes in the well are still a function of position. Also, one can solve for the flow in the bore during a complete shut in to determine the effects of phase redistribution which is not possible with a steady state model. It should be noted that a transient reservoir model cannot be used to model the wellbore flow by assuming 100% porosity. The nature of the flow in the bore at early times is characterized by a wavelike equation while reservoir models are controlled by a diffusion like equation because of the assumption of Darcy flow.

Governing Equations

The equations solved in the program are

$$\text{mass, } \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x} (\rho v) = 0; \tag{1}$$

$$\text{momentum, } \frac{\partial}{\partial t} (\rho v) + \frac{\partial}{\partial x} [\alpha \rho_g v_g^2 + (1-\alpha) \rho_f v_f^2] + \frac{\partial P}{\partial x} + \rho g + \frac{f \rho v^2}{4r} = 0; \text{ and} \tag{2}$$

$$\text{energy, } \frac{\partial}{\partial t} (\rho e) + \frac{\partial}{\partial x} [\alpha \rho_g v_g e_g + (1-\alpha) \rho_f v_f e_f] = - P \left\{ \frac{\partial}{\partial x} [\alpha v_g + (1-\alpha) v_f] \right\} + \frac{H}{2r} (T - T_r) \tag{3}$$

Note that the mass and momentum equations have been subtracted out from the energy equation so that the equation is written in terms of specific energy only. The last equation is equivalent to

$$\frac{\partial}{\partial t}\left[(\rho e) + \frac{1}{2}\alpha\rho_g v_g^{\,2} + \frac{1}{2}(1-\alpha)\rho_f v_f^{\,2}\right] + \frac{\partial}{\partial x}\left[v_g \rho_g \alpha_g \left(h_g + v_g^{\,2}/2 + g\right)\right]$$

$$+ \frac{\partial}{\partial x}\left[v_f(1-\alpha_f)\rho_f \left(h_f + v_f^{\,2}/2 + g\right)\right] + \frac{H}{2r}\left[T - T_r\right] = 0$$

The density is related to the pressure and energy by the equation of state, $\rho = \text{fn}(P,e)$ in the liquid water, two phase, or steam region, assuming local thermodynamic equilibrium. Given the pressure, the temperature will be known for a flashing system. Also ρ_g, ρ_f, e_g, and e_f are a function of the pressure alone. Using the pressure and the specific energy, the quality can be determined.

Solution Procedures

The numerical approach is to write the above equations in a finite difference form and to treat terms that would impose severe time restrictions, if solved explicitly, in an implicit fashion. Other terms are evaluated explicity for ease and computational efficiency. The continuity equation (Equation 1) is written as

$$\frac{\rho_i^{\ell+1} - \rho_i^{\ell}}{\Delta t} = -\left[\frac{(\rho v)_{i+1/2}^{\ell+1} - (\rho v)_{i-1/2}^{\ell+1}}{\Delta x}\right] \qquad [4]$$

where the expression for $(\rho v)^{\ell+1}$ is obtained from the momentum equation (Equation 2). The momentum equation is written as:

$$\frac{(\rho v)^{\ell+1}_{i+1/2} - (\rho v)^{\ell}_{i+1/2}}{\Delta t} = - \frac{[\rho_f v_f^{\,2}\,(1-\alpha)]^{\ell}_{j} - [\rho_f v_f^{\,2}\,(1-\alpha)]^{\ell}_{j-1}}{\Delta x} \qquad [5]$$

$$- \frac{[\rho_g v_g^{\,2}\alpha]^{\ell}_{j'} - [\rho_g v_g^{\,2}\alpha]^{\ell}_{j'-1}}{\Delta t} - \frac{P^{\ell+1}_{i+1} - P^{\ell+1}_{i}}{\Delta x} - \rho_{i+1/2}\,g - \frac{f(\rho v)^2_{i+1/2}}{4r}$$

where $j = i + 1/2$ if $v_f(i + 1/2) > 0$ and $j = i + 3/2$ if $v_f(i + 1/2) < 0$.

Similarly $j' = i + 1/2$ if $v_g(i + 1/2) > 0$ and $j' = i + 3/2$ if $v_g(i + 1/2) < 0$.

The energy equation (Equation 3) is written as:

$$\left(\frac{\rho^{\ell+1}_{i} + \rho^{\ell}_{i}}{2}\right)\left(\frac{e^{\ell+1}_{i} - e^{\ell}_{i}}{\Delta t}\right) = - \frac{(\rho_f v_f)^{\ell}_{i+1/2}}{\Delta x}\left\{\begin{matrix}(1-\alpha_i)(e_{f_i} - e_i)^{\ell} \\ (1-\alpha_{i+1})(e_{f_{i+1}} - e_i)^{\ell}\end{matrix}\right\}$$

$$+ \frac{(\rho_f v_f)^{\ell}_{i-1/2}}{\Delta x}\left\{\begin{matrix}(1-\alpha_{i-1})(e_{f_{i-1}} - e_i)^{\ell} \\ (1-\alpha_i)(e_{f_i} - e_i)^{\ell}\end{matrix}\right\} - \frac{(\rho_g v_g)^{\ell}_{i+1/2}}{\Delta x}\left\{\begin{matrix}\alpha_i(e_{g_i} - e_i)^{\ell} \\ \alpha_{i+1}(e_{g_{i+1}} - e_i)^{\ell}\end{matrix}\right\}$$

$$+ \frac{(\rho_g v_g)^{\ell}_{i+1/2}}{\Delta x}\left\{\begin{matrix}\alpha_{i-1}(e_{g_{i-1}} - e_i)^{\ell} \\ \alpha_i(e_{g_i} - e_i)^{\ell}\end{matrix}\right\} - P_i\left[\frac{(\alpha v_g)_{i+1/2} - (\alpha v_g)_{i-1/2}}{\Delta x}\right]$$

$$- P_i\left[\frac{[(1-\alpha)v_f]_{i+1/2} - [(1-\alpha)v_f]_{i-1/2}}{\Delta x}\right]^{\ell} + \frac{H}{2r_W}\,(T_{res} - T_w)^{\ell}$$

Where the $\{\ \}$ appear means to take the top quantity if the velocity in front of the bracket is positive, but the bottom value if that velocity is negative. The last term is the heat loss out of the wellbore. The density is written in terms of ΔP and Δe:

$$\rho_i^{\ell+1} - \rho_i^{\ell} = \left(\frac{\partial \rho}{\partial P}\right)_e^{\ell'} (P_i^{\ell+1} - P_i^{\ell}) + \left(\frac{1}{\rho}\frac{\partial \rho}{\partial e}\right)_P^{\ell'} \rho(e_i^{\ell+1} - e_i^{\ell}) \qquad [7]$$

where ℓ' is the old time level ℓ unless the calculated density is too far from the equilibrium density. In that case, ℓ' means to take some average of the derivatives at the old and new time levels. All four equations are combined to yield an expression for the new pressure in the form

$$[-2+r]P_i^{\ell+1} + P_{i+1}^{\ell+1} + P_{i-1}^{\ell+1} = rP_i^{\ell} + fn(\rho^{\ell}, v) + r\ [\rho(e_i^{\ell+1} - e_i^{\ell})] \qquad [8]$$

where $r = (\Delta x/\Delta t)^2(\partial\rho/\partial P)_e$ and $r' = (\Delta x/\Delta t)^2(1/\rho)(\partial\rho/\partial e)_P$. Once the new pressure is determined, one can evaluate the new density using equations 6 and 7. Given the new density, the energy at time level $\ell+1$ is determined using equation 6 and the new velocities are calculated using equation 4.

The heat loss out of the wellbore is given in Equation 6 by the term $H(T_r(r_w) - T_w)/2r_w$, where $T_r(r_w)$ is the temperature at the wall of the wellbore. This temperature is a function of time. At each nodal point in the well, the temperature change in the surrounding rock is calculated by solving a finite difference approximation of the radial conduction equation. At a distance RMAXT, a linear geothermal gradient from TMIN to TMAX is assumed constant. RMAXT, TMIN, and TMAX are input parameters. The equation solved at every nodal point is:

$$T_j^{\ell+1} = T_j^{\ell} + \frac{2\ \Delta t}{(r_{j+1} - r_{j-1})}\ \frac{k_t}{\rho c_\rho} \left[r_{j+1/2}\left(\frac{T_{j+1} - T_j}{r_{j+1} - r_j}\right) - r_{j-1/2}\left(\frac{T_j - T_{j-1}}{r_j - r_{j-1}}\right)\right] \qquad [9]$$

where j specifies the radial node point in the rock (a variable grid is used). The temperature in the rock is solved as a function of height and radial position. At the wall of the wellbore, the boundary condition is just the heat transfer from the fluid, $H(T_r(r_w) - T_r)/2r_w$. At the first iteration of the energy equation in the fluid, $T_r(r_w) = T_w$. The temperature of the rock is calculated implicitly next using the new temperature of the fluid in the bore. For the next iteration of the energy equation, the heat transfered to the rock is just the energy that now leaves the fluid. Because the temperature change in the rock is solved implicitly, there is no time step limitation imposed for this calculation.

A single phase reservoir model is also provided with the program. A finite difference approximation of the radial pressure diffusion equation is solved using a variable grid as in the rock temperature calculation. The equation solved is similar to Equation 9 except that the grid variation is over a larger radius, $k/\mu\phi c_t$ replaces $k_t/\rho c_p$, and P_j replaces T_j. However, the linking between the reservoir calculations and the wellbore calculation is done explicitly. The flow changes in the wellbore are calculated implicity using the current value of the sandface reservoir pressure. Then the reservoir pressure is calculated using the new value of the downhole pressure in the well, but the old value of the reservoir pressure. The exact mass flowrate that entered the wellbore leaves the reservoir in that time step calculation. When the linking was done as in the radial temperature calculation, where the heat transfer is always calculated a half time step off, oscillations developed. Therefore because this explicit method was necessary, a time step limitation is imposed.

An expression for the maximum time step has not been determined. If the calculation shows a downhole well pressure that is greater than the reservoir sandface pressure and yet the velocity is shown to still be flowing from the reservoir, the time step should be reduced. Also the first nodal point in the reservoir is usually assumed to be at $2r_w$. A skin effect can be generated depending on the position of the first few reservoir grid points.

Initial Conditions and Boundary Conditions

Initial conditions are needed to start the problem. The initial conditions needed are the downhole pressure, the specific energy flowing in from the reservoir, and the mass flowrate out of the well. This calculation gives the steady state solution for these conditions. Figure 1 illustrates the calculation of the pressure profile up the bore for well M-91 at Cerro Prieto. One can see there is an excellent match between the calculated and measured values. This comparison illustrates for this case that the slip and friction factor correlations used give reasonable results for the steady state case.

For a transient calculation, boundary conditions must also be given as a function of time. Several different boundary conditions can be used. At the bottom of the well, one can either give the bottomhole pressure as a function of time or use a reservoir model and keep the pressure far from the well constant. At wellhead, it is necessary to specify pressure, mass flowrate or volume flowrate as a function of time. It must be noted that one should give physically realistic boundary conditions. It is possible to specify a mass flowrate that actually could not be achieved in the field. Usually the wellhead pressure is held constant. For some flowrates, any slight deviation in the wellhead pressure will result in the well changing to a different flowrate while the wellhead pressure stays constant, i.e., the same wellhead pressure can result for two different mass flow rates. One could also specify a wellhead pressure that is too high, such that fluid would have to be actually injected into the bore to achieve that condition. There is no specific rule of which boundary conditions will result in a physically realistic situation, but requires one to have some understanding of what is going on. The combination of boundary conditions that are possible in the program at present are:

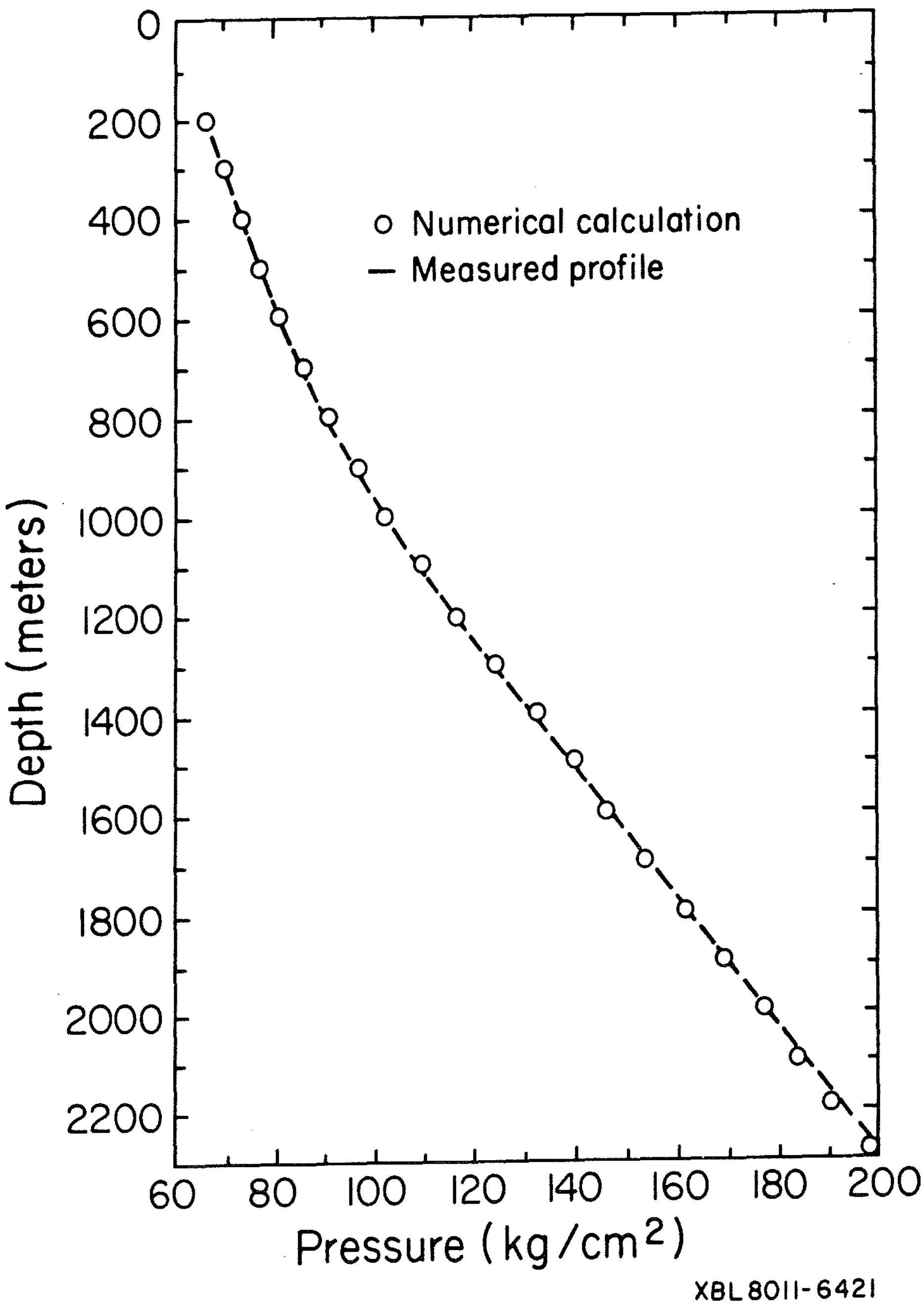

Figure 1. Comparison of the measured and calculated pressure profile for well M-91 at Cerro Prieto.

downhole pressure	and	wellhead	velocity or mass flowrate or pressure
reservoir pressure	and	wellhead	velocity or mass flowrate or pressure

Computer Code

The code WELBORE consists of a main program plus a set of subroutines. SI units are used throughout the program. Users may substitute their own subroutines if desired. The routines used are listed below.

(1) GRID - This routine sets up the grid points for calculating the temperature change around the bore. It can also be used to determine grid points for a reservoir flow calculation. The equation used to generate the grid is:

$$r(i) = r_{max}\frac{A^{(i-1)\Delta N/\Delta No}-1}{A^{1/\Delta No}-1} + r(1)$$

where ΔN is just 1/(number of grid points), r_{max} is the maximum distance from the bore that the calculation is to be made, and A and ΔNo are adjustable constants to achieve the desired grid spacing. If one wants to use a different grid spacing, one must supply to the main program RT(i), i = 1,25 and if the reservoir is included RP(i) = 1,25, and eliminate the call to the grid subroutine. The values of A, N_o, r_{max}, and the number of grid points are read into the program. Typically values of A are 1.3 to 1.8 with $\Delta N_o \approx 0.1$.

(2) INITIAL - The subroutine initializes the flow in the wellbore. When slip between the phases is included, the problem must be initialized for a mass flowrate that the well can sustain, i.e., if the flow is not self starting neither is the program. The program will dump because it will calculate a negative pressure if such a problem exists. To specify the initial steady state the following is needed, (a) downhole pressure (PBOT),

(b) specific energy flowing in from the reservoir (ERES), (c) the mass flowrate (FLOW) out of the well, and (d) the maximum and minimum temperature (TMAX, TMIN) of the geothermal gradient far from the bore. This subroutine is just the solution for the steady state case.

(3) INPRE - The subroutine initializes the reservoir pressure for a liquid filled reservoir for a given mass flowrate. The equation used for initialization is:

$$P_w = P_i - \frac{q\mu}{4\pi kh}\left[\ln\left(\frac{kt}{\mu\phi c\ r_w^{\ 2}}\right) + .809\right].$$

(4) PARAMS - When a reservoir model is used in conjuction with the wellbore model, this routine prints out the expected duration of wellbore storage and other quantities appropriate to the interaction of the well with the reservoir.

(5) FRICSLP - The subroutine calculates the slip between the phases and the friction coefficient. The friction effects are written as $f\rho v^2/4R$ and the value of f is determined according to Chisolm, 1973. A brief description follows.

The friction factor f is expressed as $f_H\rho_{eff}/\rho_f$ where f_H is the friction factor for homogeneous flow; i.e., given the Reynolds number ($\rho v 2r_w/\mu$) using the mass average velocity, v, one determines f_H using the Moody friction factor chart. Now the quantity ρ_{eff} is:

$$\rho_H\left[1 + (\Gamma^2 - 1)\left(Bx(1 - x) + x^2\right)\right]$$

where $\Gamma = (\rho_f/\rho_g)^{1/2}$, x is the flowing quality and B is a factor that depends on Γ and the total flowrate. Table 1 gives B.

The slip factor $(v_g - v_f)$ is a modified version of that given in Orkiszewski (1967) and is specified as a function of flow regime. Table 2 lists the slip regimes and the corresponding slip factor. However, such a formulation is only good for the liquid and steam both flowing vertically in

TABLE 1 - Values of B for smooth tubes

Γ	G(kg/m^{2}s)	B
	500	4.8
≤ 9.5	$\leq 500 < G < 1900$	$2400/G$
	≥ 1900	$55/G^{0.5}$
$9.5 < \Gamma < 28$	≤ 600	$520(\Gamma G^{0.5})$
	> 600	$21\ \Gamma$*
		15000
≥ 28		$\Gamma^2 G^{0.5}$

*(Taken from Chisolm, 1973)

TABLE 2

FLOW REGIME	LIMITS	SLIP
Bubble	$v_g/v < L_B$	$1.53(1-\alpha)^{1.5}\left(\frac{(\rho_f-\rho_g)\alpha}{\rho_f^2}\right)^{1/4}$
Slug	$v_g/v > L_B;\ v_{g_D} < L_S$	$0.35\ \sqrt{gD}/(1-\alpha)$
Transition	$v_g/v > L_B;\ L_S < v_{g_D} < L_m$	$\left(\frac{(L_m-v_{g_D})}{L_m-L_s}\right)0.35\ \ gD/(1-\alpha)$
Mist	$v_g/v > L_B;\ v_{g_D} > L_m$	0

where $L_B = 1.071 - .2218\ v^2/D$ but $L_B > .013$

$$L_S = 50 + 36\ v_{g_D} v_L/v_f$$

$$L_m = 75 + 84\ (v_{g_D}\ v_L/v_g)^{3/4}$$

where $v_{g_D} = \frac{v_g}{A}\left(\frac{\rho L}{g\sigma}\right)^{1/4}$

the pipe. In order to include the case of a well that is shut in for a buildup test, the slip factor must be given as a function of α. The slip must be 0 when $\alpha = 0$ or 1. When $v_\ell < 0$, the slip has been expressed as $5.5\alpha^3(1-\alpha)^{1/3}$ which is of the form used in the drift flux model. However, this model is purely speculative and further work must be done here.

(6) HCOEFF - A routine to calculate the heat transfer coefficient between the fluid and the wall of the bore. At present it is written as $0.023\ (\rho v 2r_w/\mu)^{0.8}$ (see Holman, 1976). The value of this coefficient does not usually control the rate of heat transfer because the conduction in the rock is so much slower. However, a temperature profile in the rock is assumed, which sets the initial geothermal gradient at RMAXT. A temperature build up around the bore is written into the program. The temperature changes from the natural geothermal temperature at that height to the fluid temperature in the bore at the same height. If no heat transfer is of interest, one can choose the option to set HCOEFF = 0.

(7) NEWPRE - The new pressure in the bore is calculated in this routine where an equation of the form

$$[A]P^{\ell+1} = \text{fn}\ [P^\ell,\ \rho^\ell,\ v^\ell,\ \rho(e^{\ell+1} - e^\ell)]$$

is solved. The quantity $\rho(e^{\ell+1} - e^\ell)$ is also solved in this subroutine. The matrix A is tridiagonal and is inverted using subroutine ALUD.

VELDON - This routine calculates the new density given the new pressures obtained in NEWPRE and given the quantity $\rho(e^{\ell+1} - e^\ell)$. The energy at $\ell+1$ is calculated here as well as the new velocities in the bore.

CHECK - A routine to determine how far the calculated density has drifted from the equilibrium density. The new density is calculated using the expression $\Delta\rho = (\partial\rho/\partial P)\Delta P + (\partial\rho/\partial e)\Delta e$. The derivatives are evaluated at the old time level unless the density $\rho^{\ell+1}$ is too far from that calculated by $\rho = \rho(P^{\ell+1}, e^{\ell+1})$. When the two densities differ by more than a few percent, an average of the new and old derivatives is used and the time step is recalculated.

PRERES - A routine to calculate the pressure drop in the reservoir. Several layers can be used but only a liquid filled reservoir is solved at present. A two-phase model will be included in a later version. The basic radial diffusion equation is solved.

TEMRES calculates the temperature change surrounding the wellbore. Only the radial gradient equation is solved.

SPRINT2 - A routine to print out the variables at the time specified.

EQOFS - A function to calculate the thermodynamic quantities for a steam/water or water region given the pressure and energy. This function routine could have been combined with the next routine RDRO.

RDRO calculates the thermodynamic quantities e_f, e_g, ρ_f, ρ_g, and α, given the pressure and energy. It also calculates $(\partial\rho/\partial P)_e$ and $(1/\rho)(\partial\rho/\partial e)_P$ in the steam/water or steam only or water only regions.

ALUD - A routine to invert a tri-diagonal matrix.

VARIABLES to be Read In

The input and output of the program were set up primarily for specifying the mass flowrate at wellhead although the other options of giving pressure or volume flowrate are available.

RADIUS - inner radius of wellbore (meters)

LENGTH - length of wellbore (meters)

ERES - energy per unit mass from the reservoir ($e = h-P/\rho$) (J/kg)

FLOW - initial mass flowrate per unit area, ρv (kg/m^2-s)

FLOWC - the value to which the flowrate will be changed (kg/m^2-s)

CONDUC - thermal conductivity of rock surrounding wellbore (W/m-c)

ALPHAR - thermal diffusivity of rock surrounding wellbore (m^2/s)

TMAX - maximum temperature of geothermal gradient (^oC)

TMIN - minimum temperature of geothermal gradient (^oC)

RMAXT - distance from well where it is assumed the natural geothermal gradient exists (meters)

AKT - constant A in grid transformation equation used for calculating the grid used in the temperature change outside the bore; typical values are 1.3 to 1.8

DNOT - constant ΔN_o in grid transformation equation for the temperature calculation outside the bore

MAX - maximum number of nodes in bore

NNODES - number of points where fluid flows from a reservoir into the well; if a reservoir is not used but the downhole pressure is specified, NNODES should be set to 1

MAXT - maximum number of points used in temperature calculation around bore (if greater than 25, the radial grid matrix must be increased)

MAXP - maximum number of points used for reservoir calculation; if no reservoir model is used the number will not be used (if greater than 25, the radial pressure grid must be increased)

DT - time step used (A restriction on the time step does exist because of the explicit calculation of the energy convection terms. The time step is approximately limited by $\Delta t < \Delta x/v$ but no formal derivation has been made. A time step restriction also exists because of the explicit coupling of the reservoir and the wellbore.)

TEND - the time at which the calculation is to end

TPRINT - the time interval at which you want a printout of the properties

TCHANGE - the time when the flowrate will be changed (Because the method of the initialization and the transient calculation differ slightly, it is best to run the program until $t \approx 5$ minutes without changing the initial flowrate to steady out any differences.)

IOPT1 - option to specify boundary condition at bottom of well;

if IOPT1 = 1, a reservoir model is used; at present the reservoir model is liquid filled only

if IOPT1 = 2, the downhole pressure must be specified as a function of time

IOPT2 - option to specify boundary condition at the top of the well:

if IOPT2 = 1, the mass flowrate per unit area will be given as a function of time;

if IOPT2 = 2, the pressure at wellhead is to be given as a function of time;

if IOPT2 = 3, the volume flowrate per unit area is to be given as a function of time;

(As mentioned above, one must be careful that physically realistic boundary conditions are given. Numerical solutions may exist that cannot be achieved in the field.)

IOPT3 - option to specify the heat transfer:

if IOPT3 = 1, the heat transfer coefficient is set equal to 0.0; otherwise the heat tansfer coefficient is as specified above

The wellhead and downhole pressure is read in as a function of time as needed.

TMBND (1, I) is the time

TMBND (2, I) is the wellhead condition

TMBND (3, I) is the bottom hole pressure if used (otherwise set equal to 0.0).

All parameters are read in at the beginning of the program except the boundary conditions which are read in as a function of time when needed.

The input structure is given here by listing the read statements with the format statement.

```
      READ 1000, RADIUS, LENGTH, ERES, FLOW, FLOWC
      READ 1000, CONDUC, ALPHAR, TMAX, TMIN, RMAXT, AKT, DNOT
      READ 1010, MAX, NNODES, MAXT, MAXP
      READ 1000, DT, TEND, TPRINT, TCHANGE
      READ 1010, IOPT1, IOPT2, IOPT3
      If (IOPT1.EQ.2) to to 20
      READ 1000, KH(I),I = 1, NNODES
      READ 1000, PBOT, MU, FEECH, RMAXP, AKP, DNOP
   20 CONTINUE
```

```
READ 1020, (TMBND (1,1), TMBND (2,1, TMBND (3,1))
```

(note: when the TIME is greater than TMBND (1,1) the next set of boundary conditions is read in.)

```
1000 FORMAT (7E10.4)

1010 FORMAT (7I10)

1020 FORMAT (F10.4, 2E10.5)
```

If a reservoir model option is chosen, the following additional quantities must be read in before reading in the boundary conditions.

KH(I) - the permeability thickness factor of the reservoir where I = 1, NNODES; by specifying different values of KH, a layered reservoir model can be used.

PBOT - pressure at bottom of well; if a reservoir model is used, one must have the pressure at some point in the reservoir

MU - viscosity of fluid in reservoir

FEECH - ϕch where ϕ is the porosity, c is the compressibility of the reservoir and h the height of the reservoir

RMAXP - a maximum distance from wellbore that the reservoir calculation is done (The pressure is kept constant at this point.)

AKP - a constant factor in grid calculation, similar to AKT but for the reservoir grid here

DNOP - constant factor, ΔN_o in grid calculation, similar to DNOT but for the reservoir grid

The output of the program is fairly self explanatory except for MU, FEECH, KTOTAL, and KMUCO. The first two terms are defined above while KMUCO is $k/\mu c\phi$ and KTOTAL = $\Sigma kh(i)$. Also the well to reservoir time value is a non-dimensional time indicating the importance of initial transients in the wellbore. When this quantity is on the order of 1 or less, the initial slope of log P vs. log t will not be unity (see Miller, 1979).

The other variables used in the main program are listed in case the user wants to substitute her/his own routine.

DRODE - $\frac{1}{\rho}\left(\frac{\partial\rho}{\partial e}\right)_P$ at time level ℓ+1

DRODEO - $\frac{1}{\rho}\left(\frac{\partial\rho}{\partial e}\right)_P$ at time level ℓ

DRODP - $\left(\frac{\partial\rho}{\partial P}\right)_e$ at time level ℓ+1

DRODPO - $\left(\frac{\partial\rho}{\partial P}\right)_e$ at time level ℓ

E(I) - specific energy of the fluid at nodal point I at time level ℓ+1

EF(I) - specific energy of saturated liquid at nodal point I

EG(I) - specific energy of saturated steam at nodal point I

EO(I) - specific energy of the fluid at the time level ℓ and at point I

FLOWO - mass flowrate per unit area at the old time level

FRIC(I) - friction factor at the nodal point I

G - gravitational acceleration ($9.8 m/s^2$)

PRES2(I,J) - pressure in the reservoir; I corresponds to the radial position, J to the depth

PTOP - pressure in the well at the surface

P2(I) - pressure in the wellbore at position I and at time level $\ell + 1$

RHO(I) - density of the fluid at time level ℓ and position I

RHO2(I) - density of the fluid at time level $\ell + 1$ and position I

RHOF(I) - density of saturated liquid at position I

RHOG(I) - density of saturated steam at position I

RP(I) - radial position in the reservoir for the pressure calculations

RT(I) - radial position in the rock surrounding the bore needed for the heat loss calculation

SLIP(I) - gas velocity minus the liquid velocity

T(I) - temperature in the wellbore at position I

TRES(I,J) - temperature in the rock surrounding the bore; I is the radial position, J is the height

TIME - current time

U(I) - mass averaged velocity at the old time level

V(I) - mass averaged velocity at the new time level

Sample Problems

The four sample problems listed below are meant to illustrate (1) the types of problems that can be solved with the program WELBORE, (2) the reason why a transient model instead of a steady state model is necesary in some cases, and (3) the structure of the input deck. Three of the cases use a reservoir model with the wellbore code to examine the types of drawdown or buildup curves that could result during a well test. Because kh/μ in a geothermal field is usually much greater than that of a petroleum reservoir, well tests can be shorter although transient effects in the wellbore may become important. The fourth example shows how the model could be used to analyze well test data.

Trouble Shooting

Please note that this program is still in a developmental state and cannot be used as a "black box". Many times the program will just dump if the boundary conditions are not realistic or if the time step used is too large. The program will not supply any error messages. Sometimes one can determine if any problem exists by comparing the calculated density with the equilibrium density (both are given in the output). If the difference between these quantities begins to drift, becoming 10 to 20 kg/m^3, the solution is probably not realistic. Also a time step limitation does exist because of the explicit coupling of the wellbore and the reservoir. If the pressure in the reservoir has dropped below that in the well and yet the flow has been calculated to be positive, the time step should be reduced.

Example 1

The first problem is a liquid filled well open to a liquid reservoir. It illustrates both the ability of the calculation to resolve very early time changes and take into acount longer time heat loss effects. One can use different time steps to consider these effects. S.I. units are used throughout the program except that the pressure change in the output has been written in psi. Two different cases were considered: one case with an initial temperature gradient in the well so energy changes in the bore will be important; and a second case with a uniform temperature in the well and no heat losses.

The well has an inner radius of .09m and a depth of 1800m. The fluid is initially not flowing. In case (a), the temperature gradient in the well is linear from $20^{o}C$ to $200^{o}C$. In case (b), the temperature in the well is constant at $200^{o}C$. The well is opened and a constant mass flowrate of 20 kg/s is maintained. In both cases, the initial bottomhole pressure is 19.5 MPa. The liquid reservoir used with the wellbore has the following characteristics: $k = 0.0272$ D, $h = 183$ m, $\mu = 0.24 \times 10^{-3}$ Pa-s, and $\phi ch = 5.5 \times 10^{-8}$ m/Pa. The input deck is given in Figure 2.

The first line gives the characteristics of the well. At 19.5 MPa and $200^{o}C$, the specific energy is 0.852 MJ/kg. The flowrate is initally 0.0 kg/m^2-s and is changed to 785.95 kg/m^2-s (20 kg/s). The second line inputs the data necessary for calculating the temperature gradient

WELBORE INPUT

0.09	1800.0	852000.0	0.0	785.95		
0.18E1	0.1E-5	0.200E3	0.20E2	0.3E1	0.18E1	0.1E0
50	5	25	25			
0.5	5.0	30.0	0.0			
1	1	2				
0.1E-11	0.1E-11	0.1E-11	0.1E-11	0.1E-11		
0.195E8	0.25E-3	0.55E-7	0.15E4	0.18E1	0.1E0	
0.00	0.0E0	0.0E0				
0.50	0.78595E3	0.0E0				
6000.0	0.78595E3	0.0E0				

Figure 2. Input data for sample problem 1.

around the well. The thermal conductivity of the rock surrounding the bore is 1.8W/m-C, the thermal diffusivity is 1×10^{-6} m^2/s, the maximum temperature is $200^{\circ}C$, minimum temperature is $20^{\circ}C$, and the temperature is assumed to remain at the initial temperature profile at 3m. The last two numbers have to do with calculating the grid spacing. The third line sets the desired number of grid calculations: 50 is the number of nodes in the wellbore, 5 is the number of connections between the reservoir and the wellbore, 25 is the number of radial grid points for the temperature calculation about the bore and 25 is the number of radial grid points for the reservoir pressure calculation if used. A number should be read in even if the reservoir model is not used. The fourth line inputs the times needed in the calculation. The time step used here is 0.5 sec, the maximum time of the calculation is 5 minutes, a full printout is given every 30 seconds, and the flowrate is changed after 0.0 sec. The fifth line gives the boundary condition options and the heat transfer option. Here the first 1 is for specifying a reservoir model, the second 1 is for giving the mass flowrate out of the well, and the 2 is given for including heat transfer effects. Because a reservoir model is used, the next data lines give the properties needed for the reservoir calculation. The first set of these lines inputs the value of kh for each nodal point where the reservoir and the wellbore are connected. The number of values of kh read in must just equal the number of connections between the well and the reservoir, five in this case. The next line inputs the downhole pressure in pascals (.195 E8), the viscosity in Pa-s (.25 E-3), the quantity ϕch in m/Pa (.55 E-7), and the information necessary to generate the grid for the reservoir calculations. The rest of the input data is just the flowrate as a function of time. The input is time (seconds), flowrate per unit area (kg/m^2-s), and a third value not used when a reservoir is specified. Any number will do but 0.0 was used here. When the downhole pressure is to be given instead of a reservoir, the third value will just be this downhole pressure.

The program was run for both an isothermal well and a well which initally had a temperature gradient down the bore (referred to as initially cold well). Figure 3 is the the printout after 30 seconds for the cold well case. The change in downhole and wellhead pressure and the total reservoir flowrate is given every other time step. Then at 30 seconds, the properties in the bore are printed out along with the temperature changes around the bore and the pressure changes in the wellbore. The printout is self explanatory.

Figure 4 plots the pressure calculations as a function of time for both cases. The downhole and wellhead pressure changes are given. For the isothermal case, once the initial disturbance of opening up the well dies out, the wellhead pressure follows the downhold pressure. It is important to notice that the initial wave disturbance lasts longer than the expected duration of wellbore storage, when wellbore storage is calculated assuming a uniform pressure change in the well as done in the petroleum industry. For the initially cold well, the wellhead pressure does not follow the downhole pressure because of heating of the fluid in the bore. However, one can also see that the downhole pressure for this case does not follow the calculation for the "isothermal" well because the flow out of the reservoir is not yet constant. Actual wellbore storage effects are not over until the temperature changes of the fluid in the well are negligible. Compressibility effects because of temperature changes far exceed those due to pressure changes. At later times the downhole pressure in the initially cold well approaches that of the isothermal case.

FROM TIME= 0. (SECONDS), TO TIME= 30.00(SECONDS)
THE CHANGE IN DOWNHOLE PRESSURE AND WELLHEAD PRESSURE EVERY 1.00(SECONDS) IS,

TIME (SECONDS)	DOWNHOLE PRESSURE (PASCALS)	DOWNHOLE PRESSURE CHANGE (PSI)	WELLHEAD PRESSURE (PASCALS)	WELLHEAD PRESSURE CHANGE (PSI)	RESERVOIR VELOCITY (M/SEC)
.50	.194776E+08	-3.2857	.130971E+07	-177.0925	.2438E+01
1.50	.192663E+08	-34.3524	.165881E+07	-125.7750	.1043E+02
2.50	.190602E+08	-64.6503	.210513E+07	-60.1664	.8431E+01
3.50	.190359E+08	-67.6276	.223204E+07	-41.5109	.3717E+01
4.50	.190703E+08	-63.1710	.209635E+07	-61.4577	.2906E+01
5.50	.190633E+08	-64.1973	.199567E+07	-76.2576	.3936E+01
6.50	.190356E+08	-68.2609	.199763E+07	-75.9695	.4349E+01
7.50	.190171E+08	-70.9806	.201870E+07	-72.8718	.4047E+01
8.50	.190098E+08	-72.0563	.201367E+07	-73.6104	.3770E+01
9.50	.190040E+08	-72.9086	.199664E+07	-76.1144	.3747E+01
10.50	.189961E+08	-74.0772	.198577E+07	-77.7118	.3796E+01
11.50	.189879E+08	-75.2828	.198134E+07	-78.3639	.3769E+01
12.50	.189810E+08	-76.2957	.197737E+07	-78.9467	.3748E+01
13.50	.189751E+08	-77.1591	.197204E+07	-79.7306	.3719E+01
14.50	.189696E+08	-77.9717	.196667E+07	-80.5197	.3708E+01
15.50	.189642E+08	-78.7570	.196216E+07	-81.1824	.3700E+01
16.50	.189592E+08	-79.4972	.195828E+07	-81.7538	.3688E+01
17.50	.189545E+08	-80.1866	.195461E+07	-82.2931	.3677E+01
18.50	.189501E+08	-80.8347	.195109E+07	-82.8107	.3668E+01
19.50	.189459E+08	-81.4506	.194779E+07	-83.2950	.3660E+01
20.50	.189419E+08	-82.0376	.194474E+07	-83.7435	.3653E+01
21.50	.189381E+08	-82.5970	.194189E+07	-84.1625	.3647E+01
22.50	.189345E+08	-83.1309	.193920E+07	-84.5576	.3641E+01
23.50	.189310E+08	-83.6418	.193667E+07	-84.9306	.3636E+01
24.50	.189277E+08	-84.1320	.193427E+07	-85.2824	.3631E+01
25.50	.189245E+08	-84.6031	.193201E+07	-85.6147	.3627E+01
26.50	.189214E+08	-85.0564	.192987E+07	-85.9292	.3623E+01
27.50	.189184E+08	-85.4933	.192784E+07	-86.2274	.3619E+01
28.50	.189155E+08	-85.9150	.192592E+07	-86.5104	.3616E+01
29.50	.189128E+08	-86.3225	.192409E+07	-86.7792	.3613E+01

Figure 3a. Output for sample problem 1 showing pressure change as a function of time; both the wellhead and downhole pressure are given.

FOR TIME OF .5000MINUTES, THE FLOWING ENTHALPY OUT OF THE WELL IS 96181.30(J/KG)
AND THE PROPERTIES IN THE WELLBORE ARE

POSITION (M)	PRESSURE (KG/M-SEC2)	ENERGY (J/KG)	DENSITY (KG/M3)	VELOCITY (M/SEC)	EQUILIBRIUM DENSITY (KG/M3)
1800.00	.227686E+07	93904.65	1000.09	.78533E+00	1000.08
1764.00	.263026E+07	110570.79	998.83	.78523E+00	998.83
1692.00	.333566E+07	143886.66	996.08	.78507E+00	996.07
1620.00	.403900E+07	177193.30	993.02	.78493E+00	993.02
1548.00	.474008E+07	210504.47	989.66	.78479E+00	989.66
1476.00	.543868E+07	243833.94	986.01	.78467E+00	986.01
1404.00	.613460E+07	277195.46	982.06	.78456E+00	982.06
1332.00	.682763E+07	310602.78	977.83	.78446E+00	977.83
1260.00	.751756E+07	344069.66	973.30	.78438E+00	973.30
1188.00	.820419E+07	377609.87	968.49	.78429E+00	968.49
1116.00	.888732E+07	411237.14	963.40	.78422E+00	963.40
1044.00	.956677E+07	444965.25	958.04	.78415E+00	958.04
972.00	.102423E+08	478807.94	952.40	.78409E+00	952.40
900.00	.109138E+08	512778.95	946.49	.78403E+00	946.49
828.00	.115810E+08	546892.04	940.31	.78397E+00	940.31
756.00	.122437E+08	581160.95	933.87	.78391E+00	933.87
684.00	.129018E+08	615599.42	927.17	.78385E+00	927.17
612.00	.135551E+08	650221.19	920.20	.78379E+00	920.20
540.00	.142034E+08	685039.99	912.99	.78373E+00	912.99
468.00	.148464E+08	720069.54	905.52	.78366E+00	905.52
396.00	.154841E+08	755323.53	897.80	.78359E+00	897.80
0.	.189114E+08	852099.12	876.85	.16174E+00	876.85

Figure 3b. Output for sample problem 1 showing the properties in the wellbore.

AT THIS TIME, THE TEMPERATURE PROFILE (C) AROUND THE BORE AS A FUNCTION OF HEIGHT AND RADIAL POSITION IS

HEIGHT(M)/RADIUS(M)	.90000E-01	.98633E-01	.11611E+00	.15149E+00	.22313E+00	.36816E+00	.66177E+00	.12562E+01
1800.00	.22068E+02	.20214E+02	.20001E+02	.20000E+02	.20000E+02	.20000E+02	.20000E+02	.20000E+02
1440.00	.62057E+02	.60212E+02	.60001E+02	.60000E+02	.60000E+02	.60000E+02	.60000E+02	.60000E+02
1080.00	.10205E+03	.10021E+03	.10000E+03	.10000E+03	.10000E+03	.10000E+03	.10000E+03	.10000E+03
720.00	.14203E+03	.14021E+03	.14000E+03	.14000E+03	.14000E+03	.14000E+03	.14000E+03	.14000E+03
360.00	.18203E+03	.18021E+03	.18001E+03	.18001E+03	.18001E+03	.18001E+03	.18001E+03	.18001E+03

AT THIS TIME, THE RESERVOIR PRESSURE (PASCALS) AS A FUNCTION OF HEIGHT AND RADIAL POSITION IS

HEIGHT(M)/RADIUS(M)	.18000E+00	.33797E+01	.85003E+01	.16695E+02	.29810E+02	.50798E+02	.84387E+02	.13814E+03
144.00	.17832E+08	.18184E+08	.18256E+08	.18262E+08	.18262E+08	.18262E+08	.18262E+08	.18262E+08
108.00	.18141E+08	.18493E+08	.18565E+08	.18572E+08	.18572E+08	.18572E+08	.18572E+08	.18572E+08
72.00	.18451E+08	.18803E+08	.18875E+08	.18881E+08	.18881E+08	.18881E+08	.18881E+08	.18881E+08
36.00	.18760E+08	.19112E+08	.19184E+08	.19190E+08	.19191E+08	.19191E+08	.19191E+08	.19191E+08
0.	.19069E+08	.19421E+08	.19493E+08	.19500E+08	.19500E+08	.19500E+08	.19500E+08	.19500E+08

Figure 3c. Ouput for sample problem 1 showing the temperature and pressure profile around the wellbore.

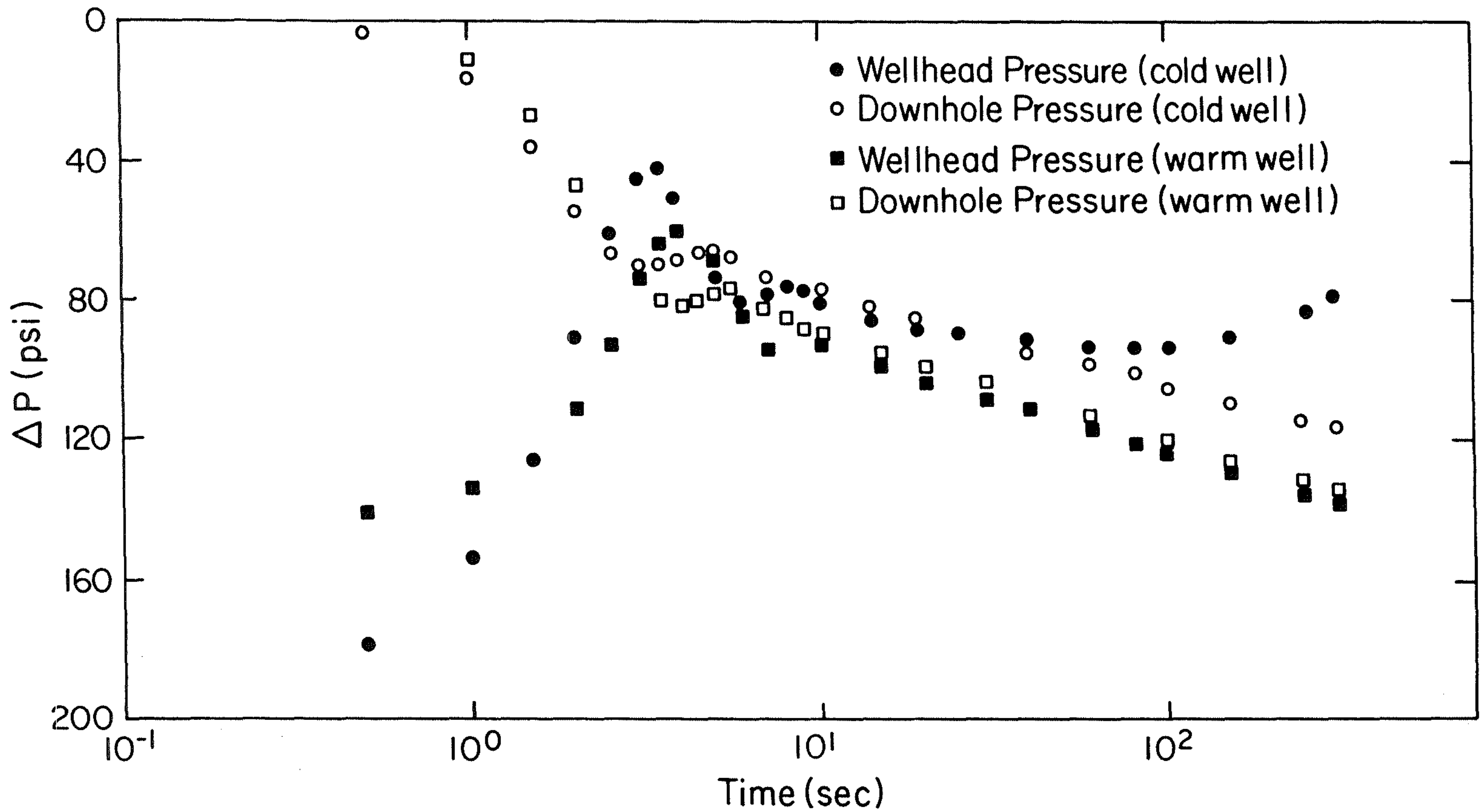

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Figure 4. Comparison of wellhead and downhole pressures for pressure drawdown curve; Two cases considered are an isothermal well (called warm well) and a well with an initial geothermal gradient (called cold well).

Example 2

The second case illustrates a calculation for a flashed fluid in the well. Calculations were done for two drawdowns and two buildups of the same change in flowrate. Figure 5 lists the input deck for the drawdown from 20 to 40 kg/s. The well is 2000m deep with a radius of 0.09m. The pressure downhole is set at 19 MPa and the reservoir temperature is 300^{o}C. The properties of the rock surrounding the bore are the same as in the first case. The grid spacing is also the same. For this case 76 node points were used in the bore with 10 connections between the well and reservoir. The time step used was 2 seconds (changes propagate slower in the flashed fluid), and the calculation was run out to 30 minutes. The properties of the reservoir were kh(i) = $1.5 \times 10^{-12} m^3$ (or a kh of $1.5 \times 10^{-11} m^3$), $\phi ch = .5 \times 10^{-6}$ m/Pa, and $\mu = 0.13 \times 10^{-3}$ Pa-s. One important difference between the first case and the second one is that even though the flow was initialized at 20 kg/s, a transient calculation was done until t = 5 minutes without changing the flowrate. In the flashed well, the slight difference between the initialization method and the transient calculation becomes important. It is best to calculate the steady state solution by running the transient calculation out until the change in downhole pressure is small. When the flowrate is changed, the downhole pressure and wellhead pressure change is related to the pressure at this time (5 minutes in this case) and not to what was initally input to the program. However the time printed out is still referenced to the start of the calculation so actual time of the drawdown or buildup is t - 300 seconds in this case.

Figure 6 shows the output just after the flowrate was changed. The point of change is noted in the printout by where the change in downhole pressure is set to 0.0. The steam and liquid velocity and the quality in place are printed out along with the pressure, energy, density, velocity, and

WELBORE INPUT

Cols. 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80

0.09	2000.0	1381400.0	786.95	1571.90		
0.18E1	0.1E-5	0.310E3	0.26E2	0.3E1	0.18E1	0.1E0
76	10	25	25			
2.0	30.0	120.0	300.0			
1	1	1				
0.15E-11	0.15E-11	0.15E-11	0.15E-11	0.15E-11	0.15E-11	0.15E-11
0.15E-11	0.15E-11	0.15E-11				
0.19E8	0.13E-3	0.50E-6	0.15E4	0.18E1	0.1E0	
0.0	0.78695E3	0.0E0				
300.0	0.78695E3	0.0E0				
302.0	0.15719E4	0.0E0				
6000.0	0.15719E4	0.0E0				

Figure 5. Input data for sample problem 2.

FROM TIME= 240.00(SECONDS), TO TIME= 360.00(SECONDS)
THE CHANGE IN DOWNHOLE PRESSURE AND WELLHEAD PRESSURE EVERY 4.00(SECONDS) IS,

TIME (SECONDS)	DOWNHOLE PRESSURE (PASCALS)	DOWNHOLE PRESSURE CHANGE (PSI)	WELLHEAD PRESSURE (PASCALS)	WELLHEAD PRESSURE CHANGE (PSI)	RESERVOIR VELOCITY (M/SEC)
242.00	.190181E+08	2.6554	.646413E+07	16.9396	.2029E+01
246.00	.190181E+08	2.6573	.646422E+07	16.9519	.2029E+01
250.00	.190181E+08	2.6594	.646430E+07	16.9643	.2029E+01
254.00	.190181E+08	2.6614	.646439E+07	16.9767	.2029E+01
258.00	.190181E+08	2.6636	.646447E+07	16.9892	.2029E+01
262.00	.190181E+08	2.6657	.646456E+07	17.0017	.2029E+01
266.00	.190181E+08	2.6679	.646464E+07	17.0142	.2029E+01
270.00	.190182E+08	2.6701	.646473E+07	17.0267	.2029E+01
274.00	.190182E+08	2.6722	.646481E+07	17.0392	.2028E+01
278.00	.190182E+08	2.6744	.646490E+07	17.0517	.2028E+01
282.00	.190182E+08	2.6764	.646498E+07	17.0640	.2028E+01
286.00	.190182E+08	2.6784	.646506E+07	17.0762	.2028E+01
290.00	.190182E+08	2.6803	.646515E+07	17.0882	.2028E+01
294.00	.190182E+08	2.6821	.646523E+07	17.1001	.2028E+01
298.00	.190183E+08	2.6838	.646530E+07	17.1117	.2029E+01
302.00	.190182E+08	-.0054	.639203E+07	-10.7776	.2066E+01
306.00	.190163E+08	-.2842	.638829E+07	-11.3272	.2795E+01
310.00	.190060E+08	-1.8038	.639092E+07	-10.9405	.4511E+01
314.00	.189873E+08	-4.5466	.639146E+07	-10.8606	.5880E+01
318.00	.189678E+08	-7.4231	.638982E+07	-11.1018	.5970E+01
322.00	.189535E+08	-9.5188	.638861E+07	-11.2803	.5410E+01
326.00	.189440E+08	-10.9143	.638932E+07	-11.1759	.4928E+01
330.00	.189370E+08	-11.9390	.639114E+07	-10.9076	.4653E+01
334.00	.189314E+08	-12.7698	.639312E+07	-10.6175	.4489E+01
338.00	.189266E+08	-13.4677	.639506E+07	-10.3320	.4374E+01
342.00	.189226E+08	-14.0660	.639707E+07	-10.0358	.4292E+01
346.00	.189190E+08	-14.5940	.639919E+07	-9.7250	.4237E+01
350.00	.189157E+08	-15.0716	.640136E+07	-9.4062	.4199E+01
354.00	.189128E+08	-15.5088	.640354E+07	-9.0855	.4170E+01
358.00	.189100E+08	-15.9111	.640571E+07	-8.7660	.4145E+01

Figure 6a. Output for sample problem 2 showing the pressure change in the well after the flowrate has been changed from 20 to 40 kg/s; both the wellhead and downhole pressures are given.

FOR TIME OF 6.0000MINUTES, THE FLOWING ENTHALPY OUT OF THE WELL IS 1376864.82(J/KG)
AND THE PROPERTIES IN THE WELLBORE ARE

POSITION (M)	PRESSURE (KG/M-SEC2)	ENERGY (J/KG)	DENSITY (KG/M3)	VELOCITY (M/SEC)	EQUILIBRIUM DENSITY (KG/M3)
2000.00	.649237E+07	1329085.04	296.86	.51936E+01	297.04
1973.33	.658031E+07	1329254.85	306.79	.50380E+01	306.98
1893.33	.685481E+07	1334718.92	329.02	.46591E+01	329.14
1813.33	.714560E+07	1340226.12	354.03	.42901E+01	354.12
1733.33	.745502E+07	1345885.86	382.24	.39304E+01	382.32
1653.33	.778592E+07	1351746.56	414.36	.35782E+01	414.43
1573.33	.814170E+07	1357922.38	451.09	.32313E+01	451.16
1493.33	.852650E+07	1364316.70	494.18	.28919E+01	494.25
1413.33	.894740E+07	1370108.79	550.34	.25631E+01	550.41
1333.33	.941746E+07	1375550.51	625.90	.22471E+01	625.91
1253.33	.995025E+07	1380983.90	716.54	.19845E+01	716.54
1173.33	.105186E+08	1381218.14	717.20	.19824E+01	717.20
1093.33	.110875E+08	1381233.22	717.93	.19803E+01	717.93
1013.33	.116570E+08	1381249.12	718.66	.19782E+01	718.66
933.33	.122270E+08	1381265.82	719.39	.19760E+01	719.39
853.33	.127976E+08	1381283.31	720.12	.19739E+01	720.12
773.33	.133688E+08	1381301.51	720.85	.19718E+01	720.85
693.33	.139405E+08	1381320.30	721.59	.19697E+01	721.59
613.33	.145129E+08	1381339.70	722.32	.19676E+01	722.32
533.33	.150857E+08	1381359.97	723.05	.19655E+01	723.05
453.33	.156592E+08	1381381.32	723.78	.19634E+01	723.78
0.	.189087E+08	1381454.74	727.96	.22317E+00	727.96

Figure 6b. Output for sample problem 2 showing the properties in the well after the surface flowrate has been increased to 40 kg/s.

POSITION (M)	GAS VELOCITY (M/SEC)	LIQUID VELOCITY (M/SEC)	SLIP (VG-VF)	QUALITY
2000.00	6.34	5.11	1.28	.64
1973.33	6.16	4.96	1.24	.62
1893.33	5.70	4.59	1.14	.59
1813.33	5.25	4.23	1.05	.56
1733.33	4.81	3.88	.96	.52
1653.33	4.39	3.54	.87	.47
1573.33	3.97	3.20	.79	.41
1493.33	3.56	2.87	.71	.35
1413.33	3.15	2.55	.63	.26
1333.33	2.41	2.25	.54	.14
1253.33	0.	1.98	0.	0.
1173.33	0.	1.98	0.	0.
1093.33	0.	1.98	0.	0.
1013.33	0.	1.98	0.	0.
933.33	0.	1.98	0.	0.
853.33	0.	1.97	0.	0.
773.33	0.	1.97	0.	0.
693.33	0.	1.97	0.	0.
613.33	0.	1.97	0.	0.
533.33	0.	1.97	0.	0.
453.33	0.	1.96	0.	0.
0.	0.	.22	0.	0.

Figure 6c. Output for sample problem 2 showing the velocity profile in the well.

AT THIS TIME, THE RESERVOIR PRESSURE (PASCALS) AS A FUNCTION OF HEIGHT AND RADIAL POSITION IS

HEIGHT(M)/RADIUS(M)	.18000E+00	.33797E+01	.85003E+01	.16695E+02	.29810E+02	.50798E+02	.84387E+02	.13814E+03
240.00	.17259E+08	.17412E+08	.17459E+08	.17485E+08	.17507E+08	.17527E+08	.17546E+08	.17565E+08
213.33	.17451E+08	.17604E+08	.17651E+08	.17677E+08	.17699E+08	.17719E+08	.17739E+08	.17757E+08
186.67	.17642E+08	.17796E+08	.17842E+08	.17869E+08	.17891E+08	.17911E+08	.17931E+08	.17949E+08
160.00	.17833E+08	.17987E+08	.18034E+08	.18061E+08	.18083E+08	.18103E+08	.18123E+08	.18141E+08
133.33	.18024E+08	.18179E+08	.18226E+08	.18253E+08	.18275E+08	.18295E+08	.18314E+08	.18333E+08
106.67	.18215E+08	.18370E+08	.18417E+08	.18444E+08	.18466E+08	.18487E+08	.18506E+08	.18524E+08
80.00	.18406E+08	.18561E+08	.18609E+08	.18636E+08	.18658E+08	.18678E+08	.18697E+08	.18716E+08
53.33	.18596E+08	.18752E+08	.18800E+08	.18827E+08	.18849E+08	.18869E+08	.18889E+08	.18907E+08
26.67	.18787E+08	.18943E+08	.18991E+08	.19018E+08	.19040E+08	.19061E+08	.19080E+08	.19098E+08
-.00	.18977E+08	.19134E+08	.19182E+08	.19209E+08	.19232E+08	.19252E+08	.19271E+08	.19289E+08

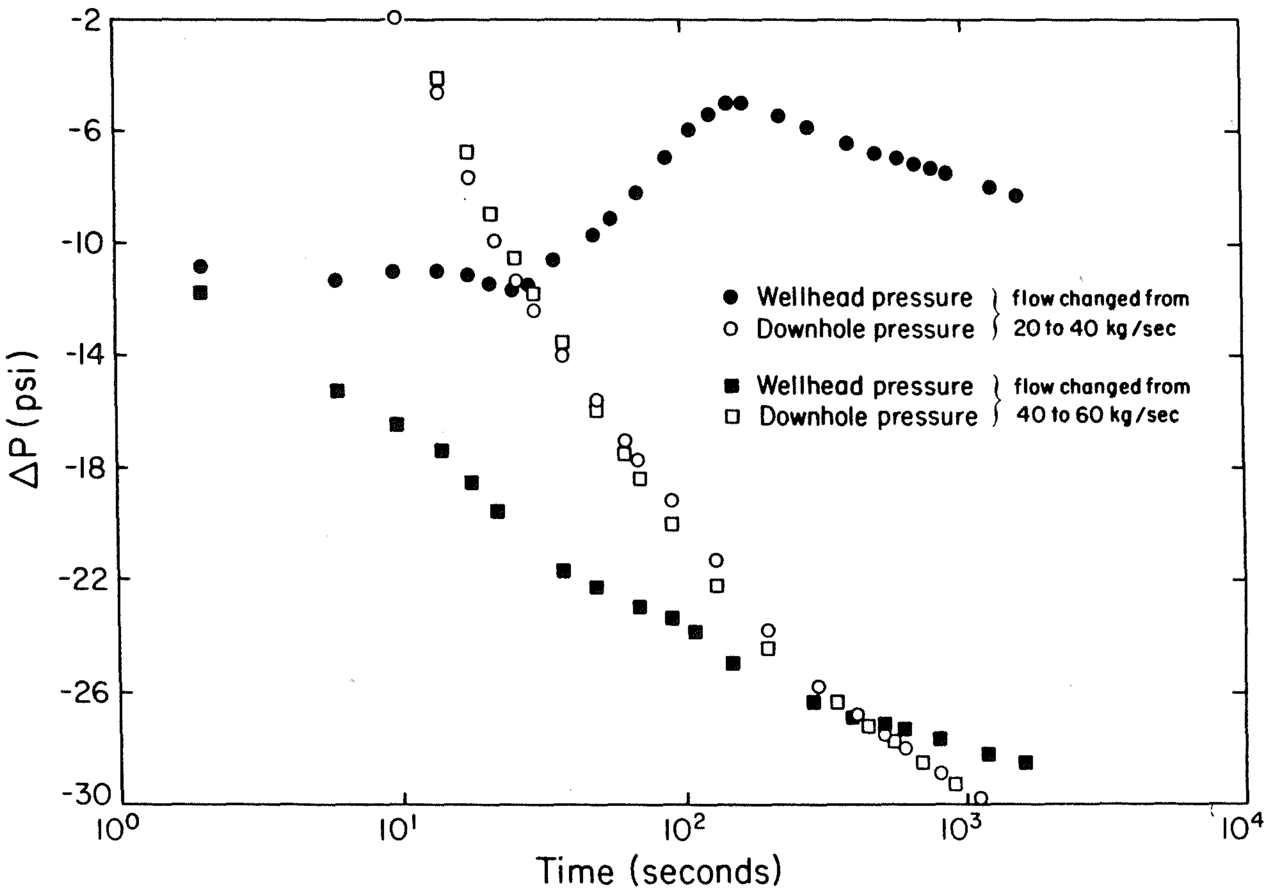
Figure 6d. Output for sample problem 2 showing the pressure profile around the wellbore.

position. Figures 7a and 7b plot the downhole and wellhead pressures as a function of time for both the drawdown and buildup cases, For all 4 cases, the downhole pressure as a function of time coincide. However, the wellhead pressure is seen to never reflect the downhole pressure change even at later times. Plotted in Figure 7c is the wellhead pressure assuming steady state for the drawdown case. The wellhead conditions are not calculated accurately with the steady state model. It is actually difficult to even calculate a steady state model when wellbore storage is important because of the changing flowrate in the wellbore and the necessity of using a single flowrate throughout the bore for the calculation. It is seen that the steady state model is not satisfactory at least when wellbore storage is important.

Example 3

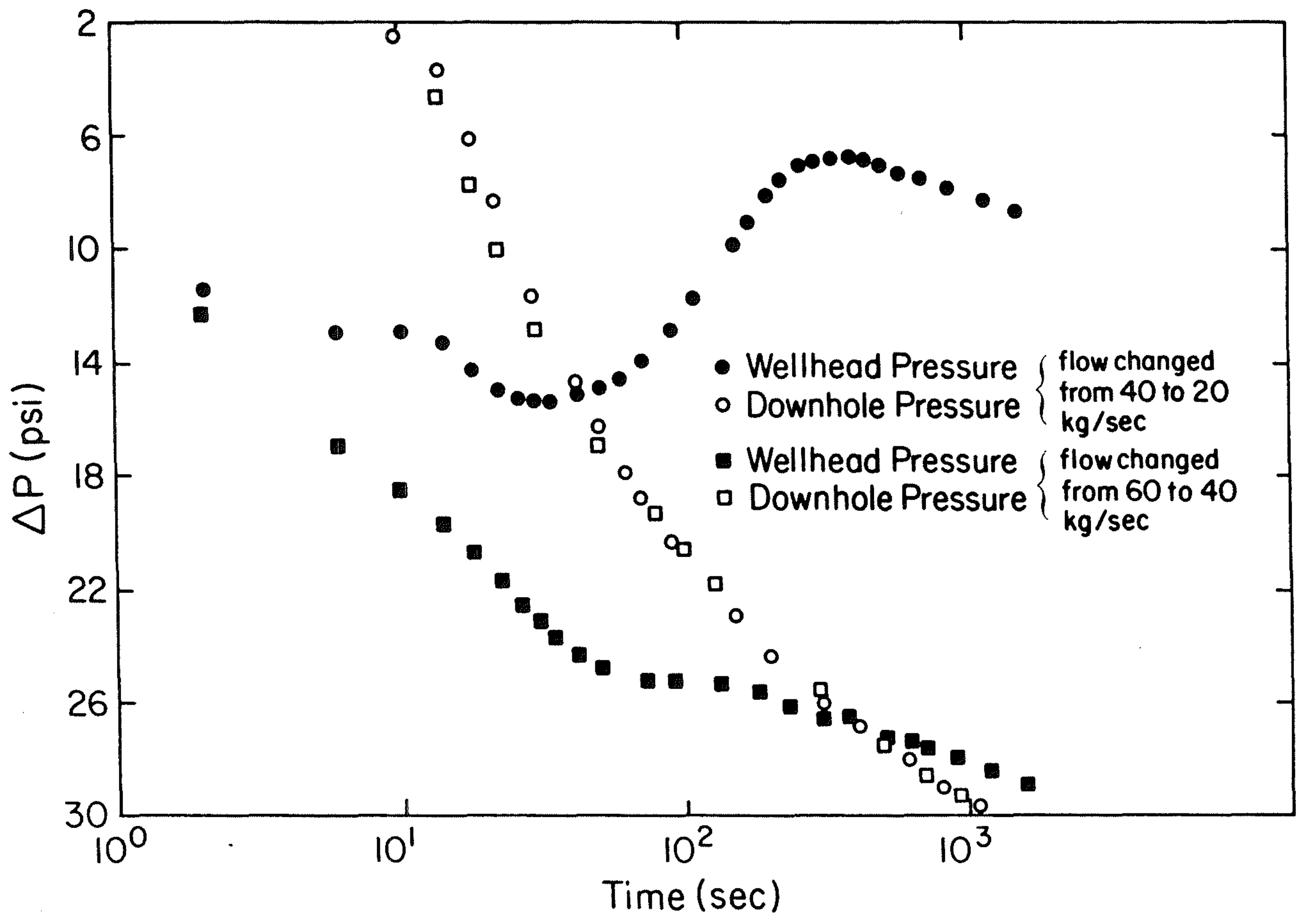
The third case is just an extension of the second example except that in this case, the well is completely shut in after being initialized at some flowrate. The program calculates the separation of steam and liquid in the wellbore. The input deck for this case is given in Figure 8. The main difference in the input of this case and the second example is that the well is now 2400m deep and the total kh of the reservoir is $0.15 \times 10^{-11} m^3$. The flow is initialized at 10.2 kg/s but a transient calculation is done for 5 mimutes to insure the changes are small. Figure 9 is the printout after the well has been shut in for 15 minutes illustrating the phase separation effects. Such a calculation would not be possible with a steady state model.

Figure 10 is a plot of the downhole pressure as a function of time for a change in flow from 10.2 kg/s to 0.0 kg/s. For reference, a case where the mass flowrate is changed from 20.4 kg/s to 10.2 kg/s is included. In the buildup plot, one sees there is a "bump" in the curve when the well is shut in. During a shut-in test, the downhole pressure may buildup faster



XBL 8011-6418

Figure 7a. Semi-log plot of pressure transient curve for two different drawdown cases.



XBL 812-2641

Figure 7b. Semi-log plot of pressure vs. time for two different buildup cases.

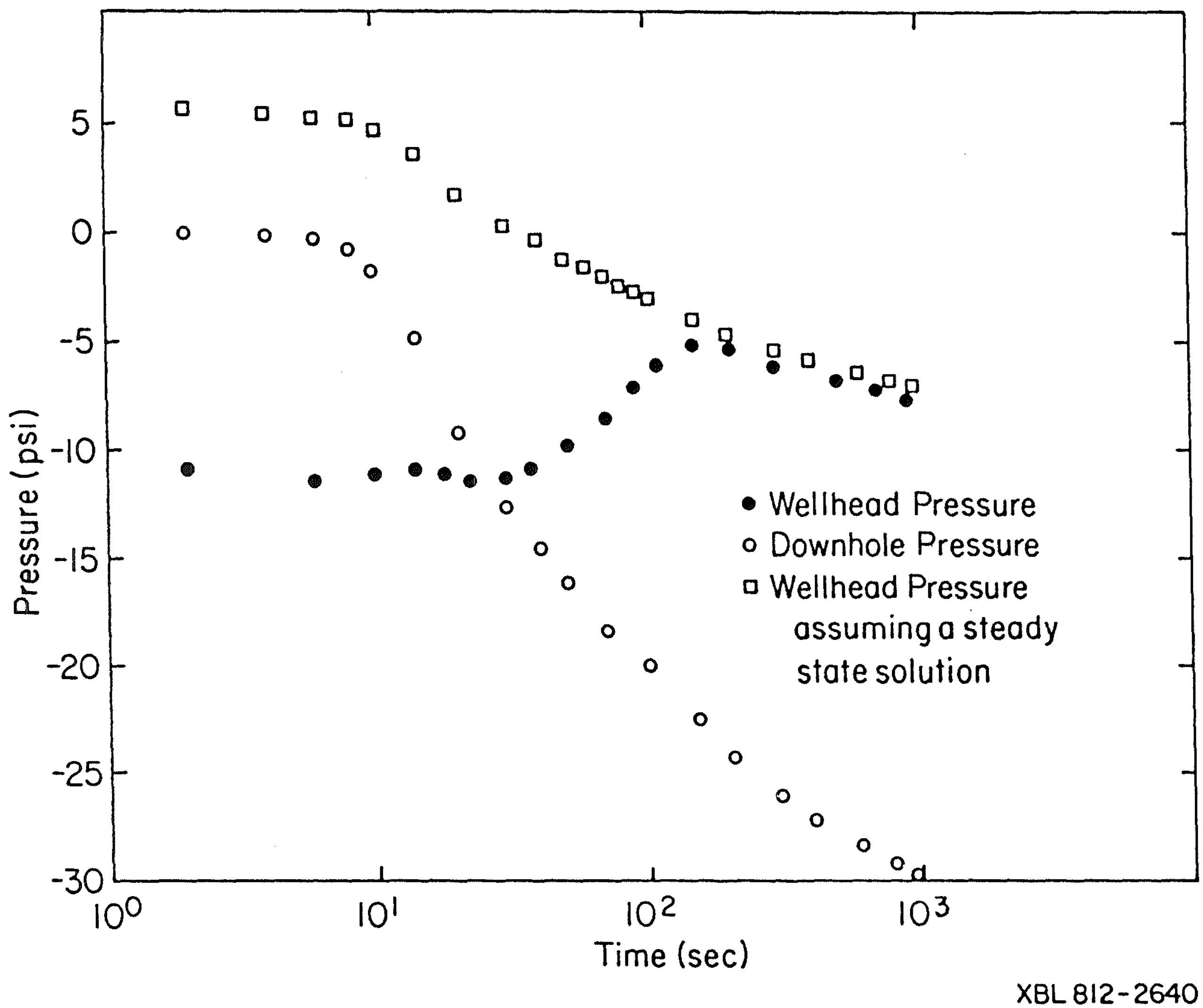


Figure 7c. Comparison of wellhead pressure calculated with a transient and a steady state numerical code; flow rate was changed from 20 to 40 kg/s.

WELBORE INPUT

0.09	2200.0	1381400.0	400.0	0.0			
0.18E1	0.1E-5	0.310E3	0.26E2	0.3E1	0.18E1	0.1E0	
76	10	25	25				
2.0	30.0	120.0	300.0				
1	1	1					
0.15E-12	0.15E-12	0.15E-12	0.15E-12	0.15E-12	0.15E-12		
0.15E-12	0.15E-12	0.15E-12					
0.19E8	0.13E-3	0.50E-6	0.15E4	0.18E1	0.1E0		
0.0	0.400E3	0.0E0					
300.0	0.400E3	0.0E0					
302.0	0.0E0	0.0E0					
6000.0	0.0E0	0.0E0					

Figure 8. Input data for sample problem 3.

FROM TIME= 960.00(SECONDS), TO TIME= 1080.00(SECONDS)
THE CHANGE IN DOWNHOLE PRESSURE AND WELLHEAD PRESSURE EVERY 4.00(SECONDS) IS,

TIME (SECONDS)	DOWNHOLE PRESSURE (PASCALS)	DOWNHOLE PRESSURE CHANGE (PSI)	WELLHEAD PRESSURE (PASCALS)	WELLHEAD PRESSURE CHANGE (PSI)	RESERVOIR VELOCITY (M/SEC)
962.00	.198577E+08	110.8259	.574752E+07	12.4167	.7983E-01
966.00	.198594E+08	111.0726	.574771E+07	12.4446	.7854E-01
970.00	.198610E+08	111.3127	.574791E+07	12.4743	.7759E-01
974.00	.198626E+08	111.5437	.574812E+07	12.5048	.7679E-01
978.00	.198641E+08	111.7680	.574831E+07	12.5332	.7600E-01
982.00	.198656E+08	111.9884	.574849E+07	12.5589	.7516E-01
986.00	.198671E+08	112.2057	.574864E+07	12.5807	.7433E-01
990.00	.198686E+08	112.4254	.574876E+07	12.5989	.7319E-01
994.00	.198701E+08	112.6442	.574890E+07	12.6200	.7237E-01
998.00	.198714E+08	112.8426	.574903E+07	12.6383	.7224E-01
1002.00	.198727E+08	113.0338	.574911E+07	12.6504	.7172E-01
1006.00	.198741E+08	113.2282	.574897E+07	12.6300	.7095E-01
1010.00	.198753E+08	113.4165	.574897E+07	12.6297	.7052E-01
1014.00	.198765E+08	113.5945	.574914E+07	12.6548	.7027E-01
1018.00	.198778E+08	113.7722	.574912E+07	12.6524	.6968E-01
1022.00	.198790E+08	113.9558	.574911E+07	12.6503	.6886E-01
1026.00	.198802E+08	114.1389	.574909E+07	12.6468	.6824E-01
1030.00	.198815E+08	114.3179	.574883E+07	12.6094	.6768E-01
1034.00	.198826E+08	114.4912	.574877E+07	12.6006	.6736E-01
1038.00	.198837E+08	114.6451	.574885E+07	12.6119	.6763E-01
1042.00	.198847E+08	114.7918	.574873E+07	12.5950	.6751E-01
1046.00	.198857E+08	114.9464	.574865E+07	12.5827	.6690E-01
1050.00	.198868E+08	115.1048	.574852E+07	12.5638	.6636E-01
1054.00	.198879E+08	115.2616	.574839E+07	12.5442	.6597E-01
1058.00	.198889E+08	115.4144	.574826E+07	12.5250	.6567E-01
1062.00	.198899E+08	115.5626	.574785E+07	12.4651	.6544E-01
1066.00	.198909E+08	115.7031	.574763E+07	12.4323	.6541E-01
1070.00	.198918E+08	115.8350	.574770E+07	12.4429	.6548E-01
1074.00	.198927E+08	115.9644	.574753E+07	12.4183	.6536E-01
1078.00	.198936E+08	116.0962	.574726E+07	12.3782	.6507E-01

Figure 9a. Output for sample problem 3 showing the wellhead and downhole pressure as a function of time.

FOR TIME OF 18.CCCOMINUTES, THE FLOWING ENTHALPY OUT OF THE WELL IS 0. (J/KG)
ANC THE PROPERTIES IN THE WELLBORE ARE

POSITION (M)	PRESSURE (KG/M-SEC2)	ENERGY (J/KG)	DENSITY (KG/M3)	VELOCITY (M/SEC)	EQUILIBRIUM DENSITY (KG/M3)
2200.00	.575841E+07	2641415.19	27.94	.56543E-02	20.91
2170.67	.576653E+07	2733341.66	28.55	.12604E-02	19.06
2082.67	.611440E+07	1247875.93	475.53	-.47975E-01	481.29
1994.67	.652457E+07	1273505.36	466.50	-.81924E-01	465.94
1906.67	.695626E+07	1278608.47	557.82	.16230E-01	558.30
1818.67	.741038E+07	1299043.41	567.40	.16425E-01	567.64
1730.67	.787902E+07	1324925.96	543.23	.16054E-01	543.64
1642.67	.836195E+07	1339516.24	581.80	.19420E-01	582.13
1554.67	.890072E+07	1348079.02	673.93	.34814E-01	674.48
1466.67	.950672E+07	1365819.61	719.30	.39625E-01	720.07
1378.67	.101255E+08	1379839.75	717.32	.39610E-01	717.14
1290.67	.107447E+08	1381246.95	718.36	.39601E-01	717.48
1202.67	.113639E+08	1381248.18	718.28	.39616E-01	718.28
1114.67	.119837E+08	1381265.71	719.08	.39607E-01	719.08
1026.67	.126042E+08	1381284.18	719.87	.39598E-01	719.87
938.67	.132253E+08	1381303.60	720.67	.39589E-01	720.67
850.67	.138472E+08	1381323.95	721.46	.39580E-01	721.46
762.67	.144697E+08	1381345.21	722.26	.39572E-01	722.26
674.67	.150930E+08	1381367.22	723.06	.39563E-01	723.06
586.67	.157169E+08	1381389.50	723.86	.39554E-01	723.86
498.67	.163415E+08	1381411.29	724.66	.39545E-01	724.66
0.	.198940E+08	1381240.13	729.29	.35076E-02	729.29

Figure 9b. Output for sample problem 3 showning the properties in the well 18 minutes after the well has been shut in.

POSITION (M)	GAS VELOCITY (M/SEC)	LIQUID VELOCITY (M/SEC)	SLIP (VG-VF)	QUALITY
2200.00	.01	0.	0.	1.00
2170.67	.38	0.	0.	1.00
2082.67	.22	-.06	.27	.39
1994.67	.22	-.09	.31	.40
1906.67	.12	.01	.13	.27
1818.67	.13	.01	.13	.25
1730.67	.14	.01	.12	.28
1642.67	.17	.02	.14	.22
1554.67	.22	.03	.18	.08
1466.67	.04	.04	.20	.00
1378.67	0.	.04	0.	0.
1290.67	0.	.04	0.	0.
1202.67	0.	.04	0.	0.
1114.67	0.	.04	0.	0.
1026.67	0.	.04	0.	0.
938.67	0.	.04	0.	0.
850.67	0.	.04	0.	0.
762.67	0.	.04	0.	0.
674.67	0.	.04	0.	0.
586.67	0.	.04	0.	0.
498.67	0.	.04	0.	0.
0.	0.	.00	0.	0.

Figure 9c. Output for sample problem 3 showing the velocity profile in the well.

AT THIS TIME, THE RESERVOIR PRESSURE (PASCALS) AS A FUNCTION OF HEIGHT AND RADIAL POSITION IS

HEIGHT(M)/RADIUS(M)	.18000E+00	.33797E+01	.85003E+01	.16695E+02	.29810E+02	.50798E+02	.84387E+02	.13814E+03
264.00	.18025E+08	.18063E+08	.18108E+08	.18191E+08	.18295E+08	.18377E+08	.18386E+08	.18386E+08
234.67	.18234E+08	.18272E+08	.18317E+08	.18400E+08	.18504E+08	.18586E+08	.18595E+08	.18595E+08
205.33	.18443E+08	.18481E+08	.18527E+08	.18609E+08	.18713E+08	.18795E+08	.18804E+08	.18804E+08
176.00	.18652E+08	.18690E+08	.18736E+08	.18818E+08	.18922E+08	.19004E+08	.19013E+08	.19013E+08
146.67	.18861E+08	.18899E+08	.18945E+08	.19027E+08	.19131E+08	.19213E+08	.19222E+08	.19222E+08
117.33	.19070E+08	.19108E+08	.19154E+08	.19236E+08	.19340E+08	.19422E+08	.19431E+08	.19431E+08
88.00	.19279E+08	.19317E+08	.19363E+08	.19445E+08	.19549E+08	.19631E+08	.19640E+08	.19640E+08
58.67	.19489E+08	.19527E+08	.19572E+08	.19655E+08	.19758E+08	.19840E+08	.19849E+08	.19849E+08
29.33	.19698E+08	.19736E+08	.19781E+08	.19864E+08	.19967E+08	.20049E+08	.20058E+08	.20058E+08
-.00	.19908E+08	.19945E+08	.19991E+08	.20073E+08	.20176E+08	.20258E+08	.20267E+08	.20267E+08

Figure 9d. Output for sample problem 3 showing the pressure profile around the wellbore.

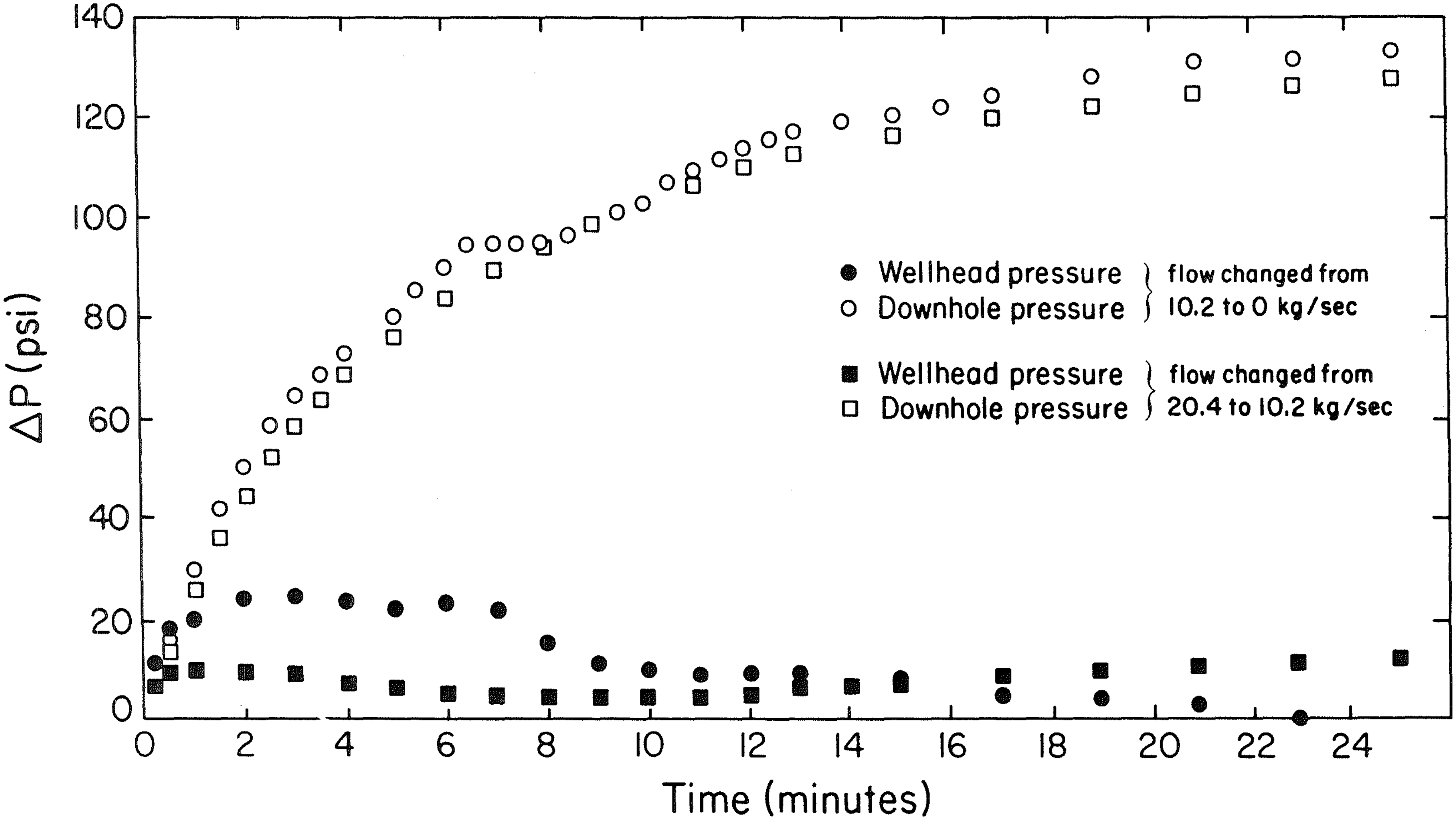


Figure 10. Plot of pressure vs. time for a complete shut in case. Included is a plot of a buildup case where the well is not shut in.

than a uniform wellbore theory predicts because of phase redistribution in the well. The fluid in the well can actually flow back into the reservoir. Such problems have usually rendered this type of data useless although attempts have been made to determine alternate data reduction methods (Fair, 1979). Now it should be recalled that the slip correlation used in this calculation, when the fluid flow is not entirely in the vertical direction, is purely speculative because of the lack of experimental data. However the computation is useful in identifying what effects in the wellbore can explain changes in pressure vs. time plots, and that such effects are not necessarily due to the reservoir itself.

Example 4

The fourth case shows how the wellbore model could be used to analyze well test data. If one measures the flowrate and downhole pressure as a function of time, the actual flow into or out of the reservoir can be calculated. One could then use a variable flow analysis method to determine the reservoir properties even when wellbore storage is still important. It may also be possible to use wellhead pressure and wellhead flowrate and then use the program to calculate downhole pressure and flowrate although this option has not yet been included in the code.

The input deck for this calculation is given in Figure 11. In this case, the first option choice on line 5 will now be given as 2 because the downhole pressure will be read in as a function of time. The well is 1500 m deep and the flowrate is changed from 20 to 40 kg/s. No properties of the reservoir need be specified because the calculation is just to eliminate the well flow as an unknown so the set of data after the option specification is eliminated. The number of connections with the reservoir is set equal to 1. However, one must input the flowrate and pressure as a function of time. The better the detail, the more accurate the calculation will be. Part of the downhole pressure as a function of time is listed.

WELBORE INPUT

```
Cols. 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80

      0.09    1500.0 1381400.0     786.0    1572.0
    0.18E1    0.1E-5   0.310E3    0.26E2     0.3E1    0.18E1     0.1E0
        76         1        25        25
       2.0      40.0     120.0       0.0
         2         1         1
       0.0   0.786E3         8
       2.0  0.1572E4 .190662E8
       6.0  0.1572E4 .190620E8
      10.0  0.1572E4 .190114E8
      14.0  0.1572E4 .189675E8
      18.0  0.1572E4 .189158E8
      20.0  0.1572E4 .188723E8
      24.0  0.1572E4 .188367E8
```

Figure 11. Part of the input data for sample problem 4.

Given the input data, the program then calculates the sandface flow rate as a function of time. Figure 12 is a plot of the calculated sandface rate for a step change in flowrate fom 20 to 40 kg/s at wellhead. This option is especially of interest when wellbore storage is significant over most of the test. Many geothermal well tests are limited in time because the available instrumentation can not be used for long times at high temperatures. It may not be possible to run a test until wellbore storage is over. However, given the downhole pressure and actual sandface flowrate, one could use the program ANALYZE (Benson and McEdwards, 1980) to obtain the properties of the reservoir.

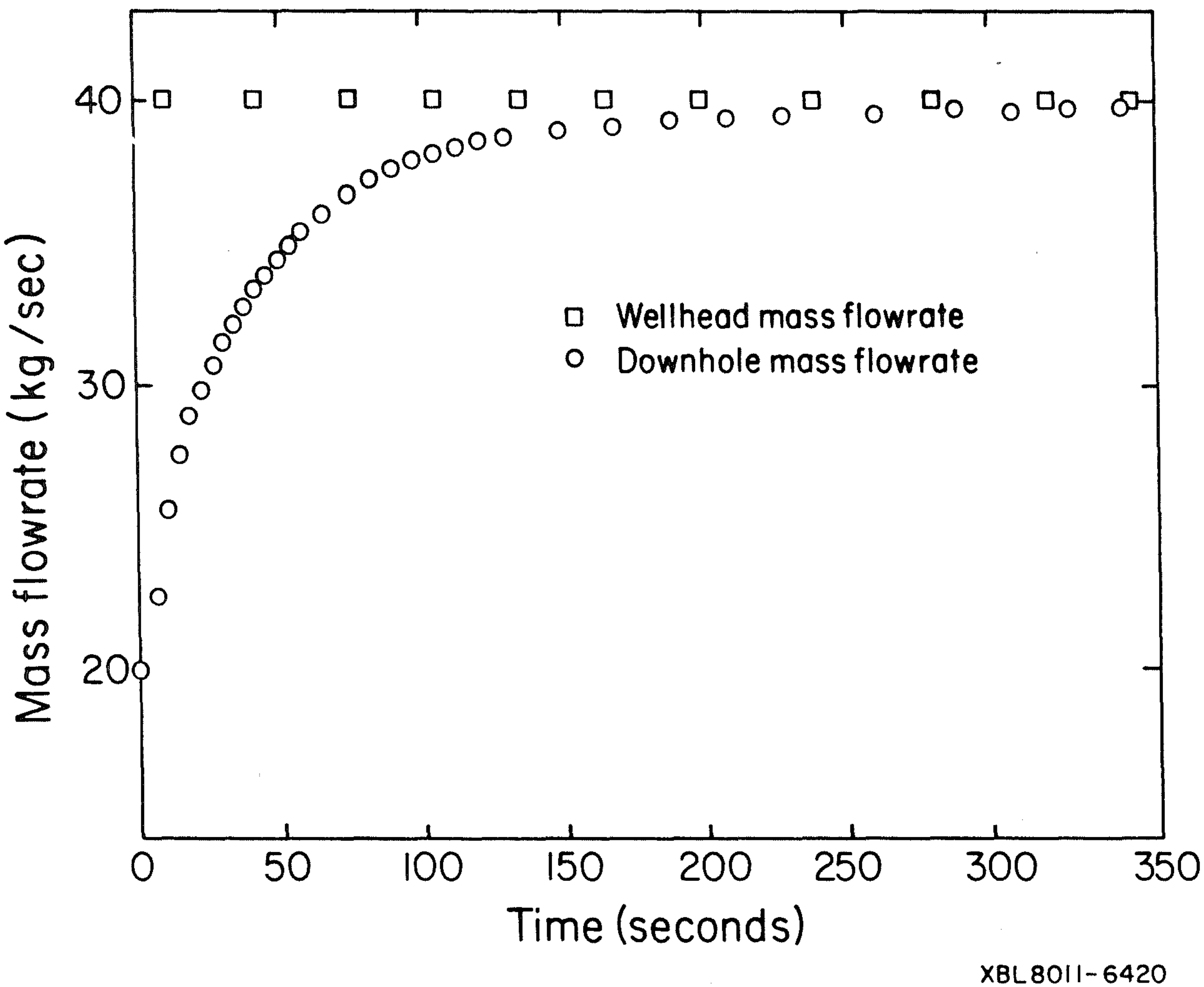


Figure 12. Wellhead and sandface mass flowrate as a function of time after the wellhead flowrate has been changed from 20 to 40 kg/s.

Nomenclature

c	compressibility of reservoir
e	mass average specific energy
e_g	specific energy of saturated steam
e_f	specific energy of saturated liuid
f	friction factor
g	gravity
h_g	specific enthalpy of saturated steam
h_f	specific enthalpy of saturated liquid
h	reservoir thicknes
H	heat transfer coefficient
k	permeability
κ_t	thermal conductivity
P	pressure
P_w	sandface pressure in well
P_i	initial pressure in reservoir
q	volume flowrate
r_w	radius of wellbore
t	time
T	temperature of fluid in wellbore
T_r	reservoir temperature
v	mass averaged velocity of fluid
v_g	velocity of steam
v_f	velocity of liuid water
x	spatial distance
α	volumetric quality in place
φ	porosity
ρ	density
ρ_g	density of saturated steam
ρ_f	density of saturated liquid water
ρ_H	homogeneous density
μ	viscosity

References

Benson, S. and McEdwards, D., ANALYZE User's Manual, LBL Report 10907, Lawrence Berkeley Laboratory, Berkeley, CA (1980).

Chisholm, D., Pressure Gradients Due to Friction during the Flow of Evaporating Two-Phase Mixtures in Smoother Tubes and Channels, Int. J. Heat Mass Transfer, 16, p. 347 (1973).

Fair, W.B., Pressure Buildup Analysis with Wellbore Phase Redistribution, presented at the 54th Annual Fall Technical Conference, Society of Petroleum Engineers of AIME, Las Vegas (1979).

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Orkiszewski, J., Predicting Two-Phase Pressure Drops in Vertical Pipe, J. Pet. Tech., p. 289 (June 1967).

Holman, J.P., Heat Transfer, McGraw Hill, p. 204 (1976).